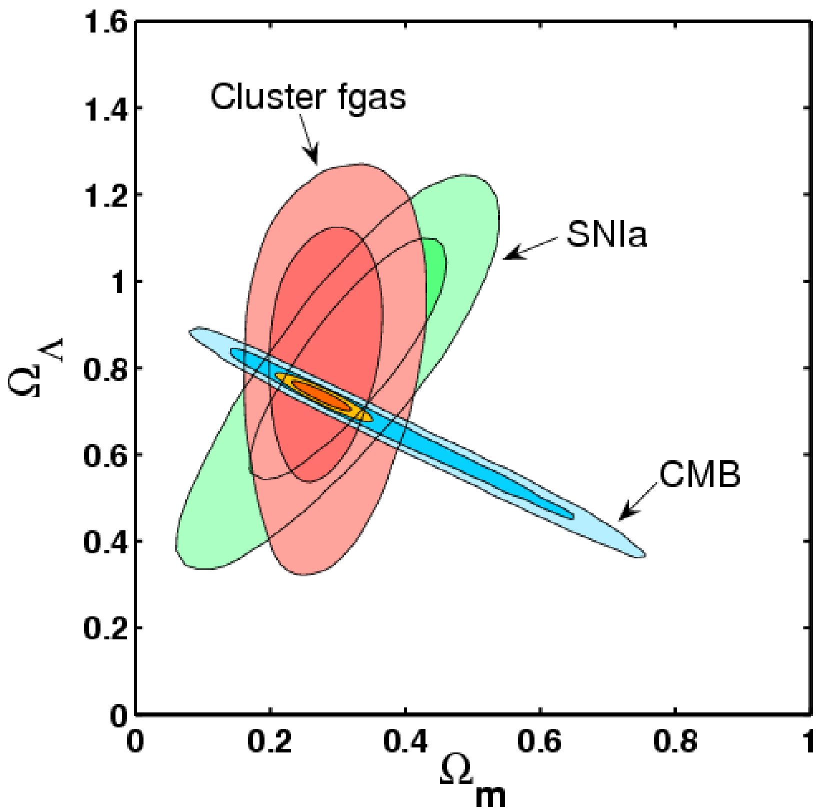
Con-X and cosmology

Steve Allen, KIPAC



In collaboration with:

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Avenues for probing cosmology with X-ray clusters

1) (Absolute) Distance Measurements**

The fgas experiment: constraints on the mean matter density Ω_m and dark energy (Ω_{de},w) from direct measurements of evolution of baryonic mass fraction in largest dynamically relaxed clusters.

Additional constraining power and systematic checks also available with SZ follow up of same target clusters.

2) Growth of cosmic structure

Counting clusters: constraints on the mean matter density Ω_m, amplitude of matter fluctuations σ_8, and dark energy (Ω_{de},w), from the evolution of the number density of X-ray luminous clusters.

Con-X will enable better calibration of cluster mass-observable scaling relations, enhancing the power of future X-ray and SZ cluster surveys.

** Con-X drives the science

Probing cosmology with X-ray clusters

1. Absolute distance measurements (the fgas experiment)

Allen et al. 2008, MNRAS, 383, 879

(See also White & Frenk ’91; Fabian ’91; Briel et al. ’92; White et al ’93; David et al. ’95; White & Fabian ’95; Evrard ’97; Mohr et al ’99; Ettori & Fabian ’99; Roussel et al. ’00; Grego et al ’00; Ettori et al. ’03; Sanderson et al. ’03; Lin et al. ’03; LaRoque et al. ’06; Allen et al. ’02, ’03, ’04.)

Under the assumption that clusters provide approximately fair samples of the matter content of the Universe,

$$\boxed{f_{baryon} = b\,\frac{\Omega_b}{\Omega_m}}$$

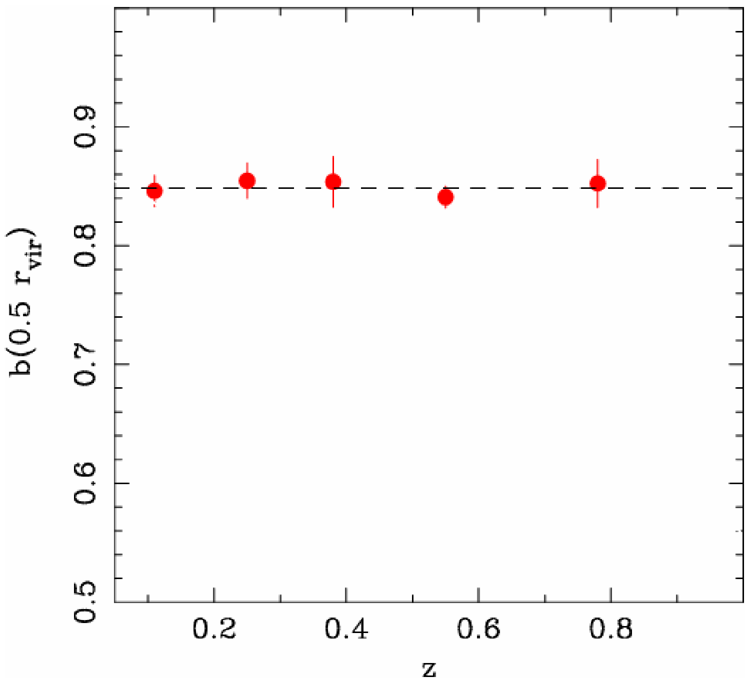
and with priors on Ω_b, h (CMB) and b (simulations), X-ray observations of large, relaxed clusters (+optical/sub-mm data) can constrain Ω_m.

Moreover, if we also have some idea how b evolves with redshift, then we can also use such observations to constrain dark energy.

Constraining dark energy with f_{gas} measurements

The measured f_{gas} values depend upon assumed distances to clusters $f_{gas} \propto d^{1.5}$. This introduces apparent systematic variations in $f_{gas}(z)$ depending on differences between reference cosmology and true cosmology.

What do we expect to observe?



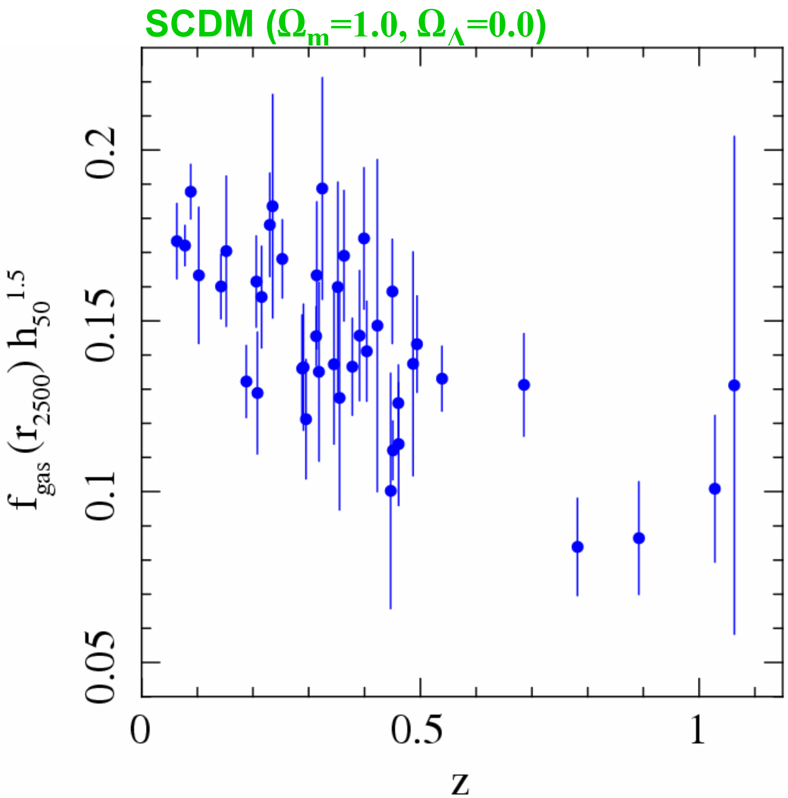
Simulations: Eke et al '98

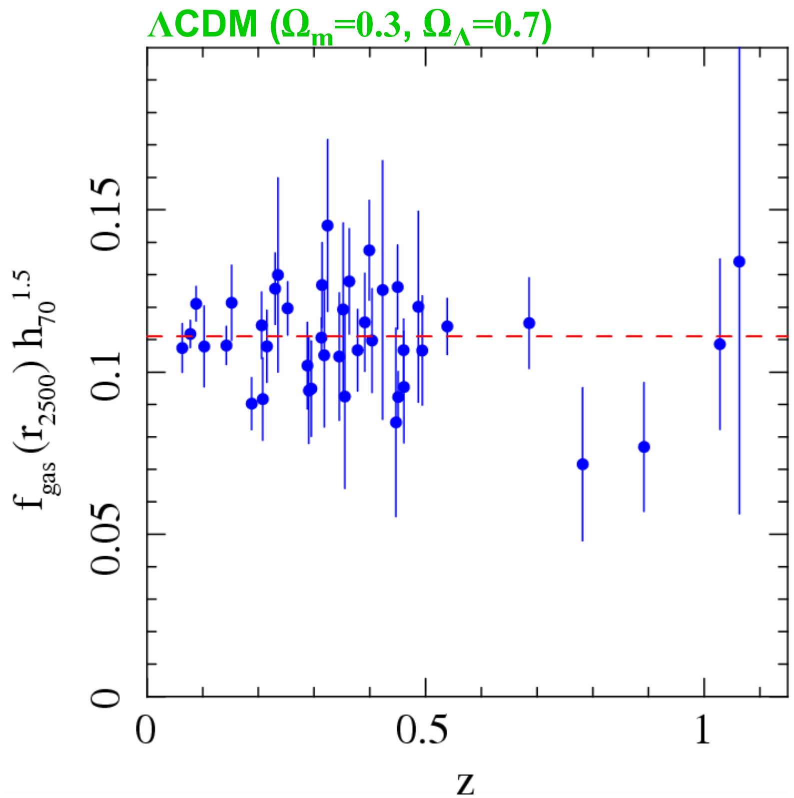
Available non-radiative simulations for large (kT>5keV) relaxed clusters suggest little/no evolution of depletion factor b(z) within z<1.

So we expect the observed $f_{gas}(z)$ values to be approx. constant with z.

(Precise prediction of b(z) arguably main task for simulations)

Chandra results on f_{gas}(z) (42 hot, relaxed clusters)





Brute-force determination of f_{gas}(z) for two reference cosmologies:

→ Inspection clearly favours ΛCDM over SCDM cosmology.

To quantify: fit data with model which accounts for apparent variation in f_{gas}(z) as underlying cosmology is varied $\rightarrow$ find best fit cosmology.

$$f_{\mathrm{gas}}(\mathrm{z}) = \frac{KA\gamma b(z)}{1+s(z)}\left(\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right)\left[\frac{d_{\mathrm{A}}^{\mathrm{LCDM}}(z)}{d_{\mathrm{A}}^{\mathrm{model}}(z)}\right]^{1.5}$$

Allowances for systematic uncertainties

Our full analysis includes a comprehensive and conservative treatment of potential sources of systematic uncertainty in current analysis.

1) The depletion factor (simulation physics, gas clumping etc.)

$b(z)=b_0(1+\alpha_b z)$ 20% uniform prior on b_0 (simulation physics)
10% uniform prior on α_b (simulation physics)

2) Baryonic mass in stars: define $s= f_{star}/f_{gas} =0.16h_{70}^{0.5}$

$s(z)=s_0(1+\alpha_s z)$ 30% Gaussian uncertainty in s_0 (observational uncertainty)
20% uniform prior on α_s (observational uncertainty)

3) Non-thermal pressure support in gas: (primarily bulk motions)

$\gamma= M_{true}/M_{X\text{-}ray}$ 10% uniform prior $1<\gamma<1.1$ (also runs with $1<\gamma<1.2$)

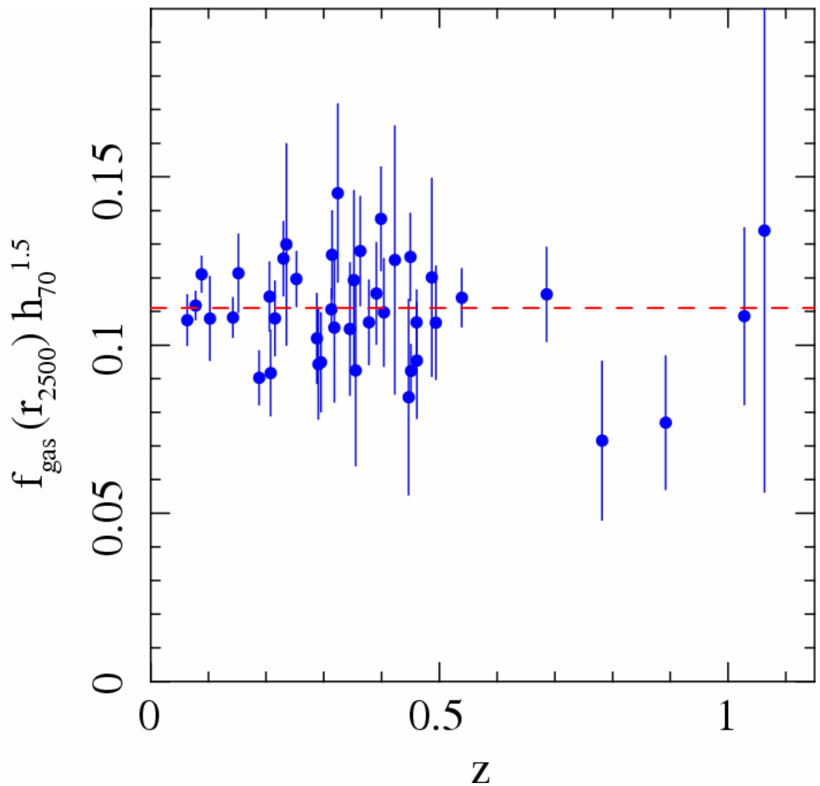
4) Instrument calibration, X-ray modelling

K 10% Gaussian uncertainty

With these (conservative) allowances for systematics

Model:

$$f_{\mathrm{gas}}(z) = \frac{KA\gamma b(z)}{1+s(z)}\left(\frac{\Omega_b}{\Omega_m}\right)\left[\frac{d_A^{\;\mathrm{LCDM}}(z)}{d_A^{\;\mathrm{model}}(z)}\right]^{1.5}$$



Results (ΛCDM)

Full allowance for systematics + standard priors:
($\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08)

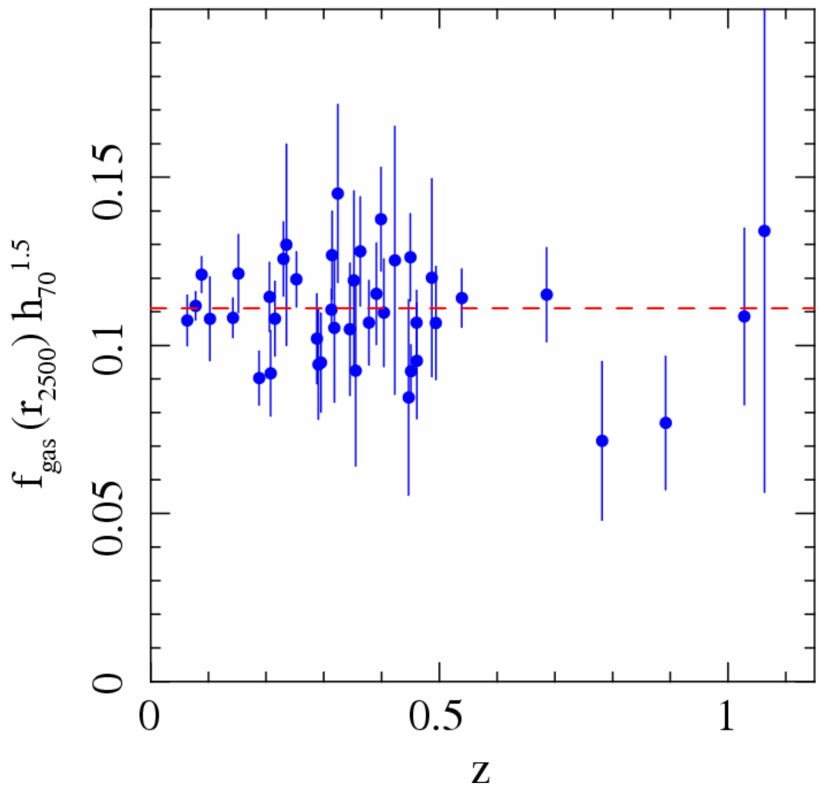
Best-fit parameters (ΛCDM):

Ω_m=0.27±0.06, Ω_Λ=0.86±0.19

(Note also good fit: χ^2=41.5/40)

Important

The low systematic scatter in the $f_{gas}(z)$ data



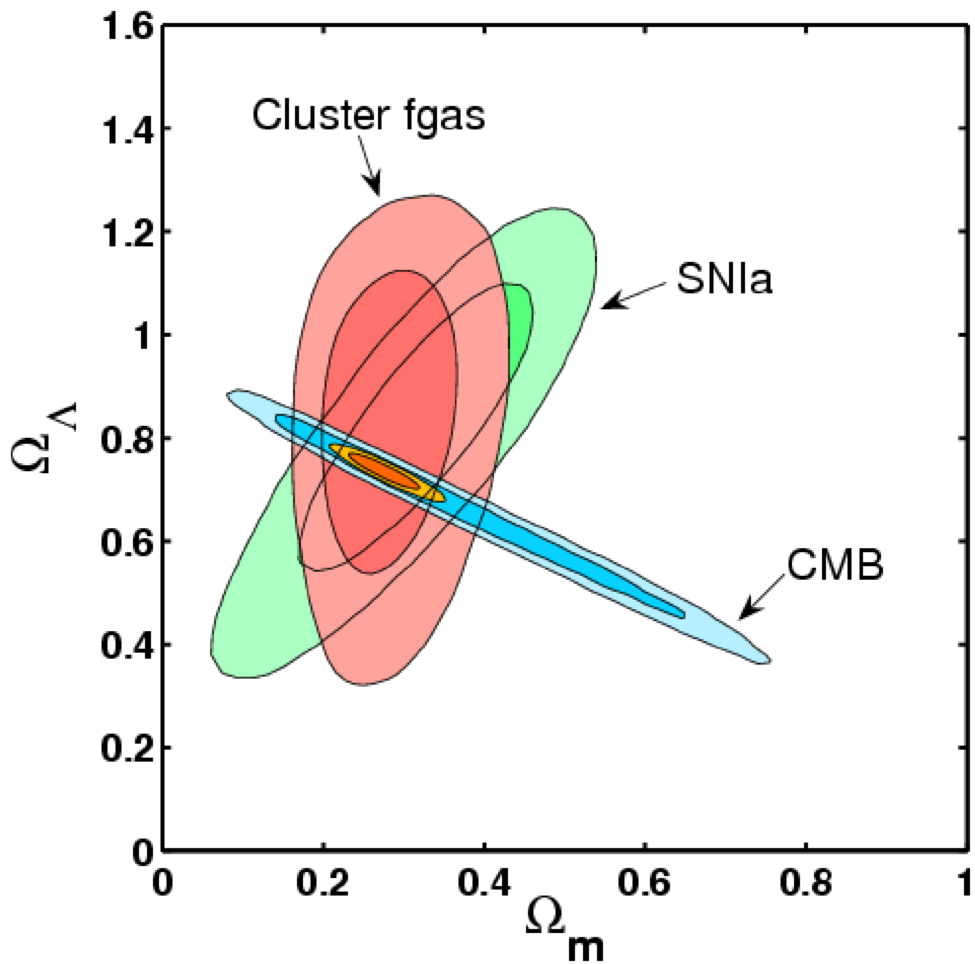
The χ^2 value is acceptable even though rms scatter about the best-fit model is only 15% in fgas, or 10% in distance.

Weighted-mean scatter only 7.2% in fgas or 4.8% in distance). c.f. SNIa, for which systematic scatter detected at ~7% level (distance).

Consistent with expectation from simulations (e.g. Nagai et al. '07)

The low systematic scatter in $f_{gas}(z)$ data offers the prospect to probe cosmic acceleration to high precision with Con-X.

Comparison of independent constraints (ΛCDM)



f_{gas} analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

CMB data (WMAP-3yr +CBI+ACBAR + prior 0.2<h<2.0)

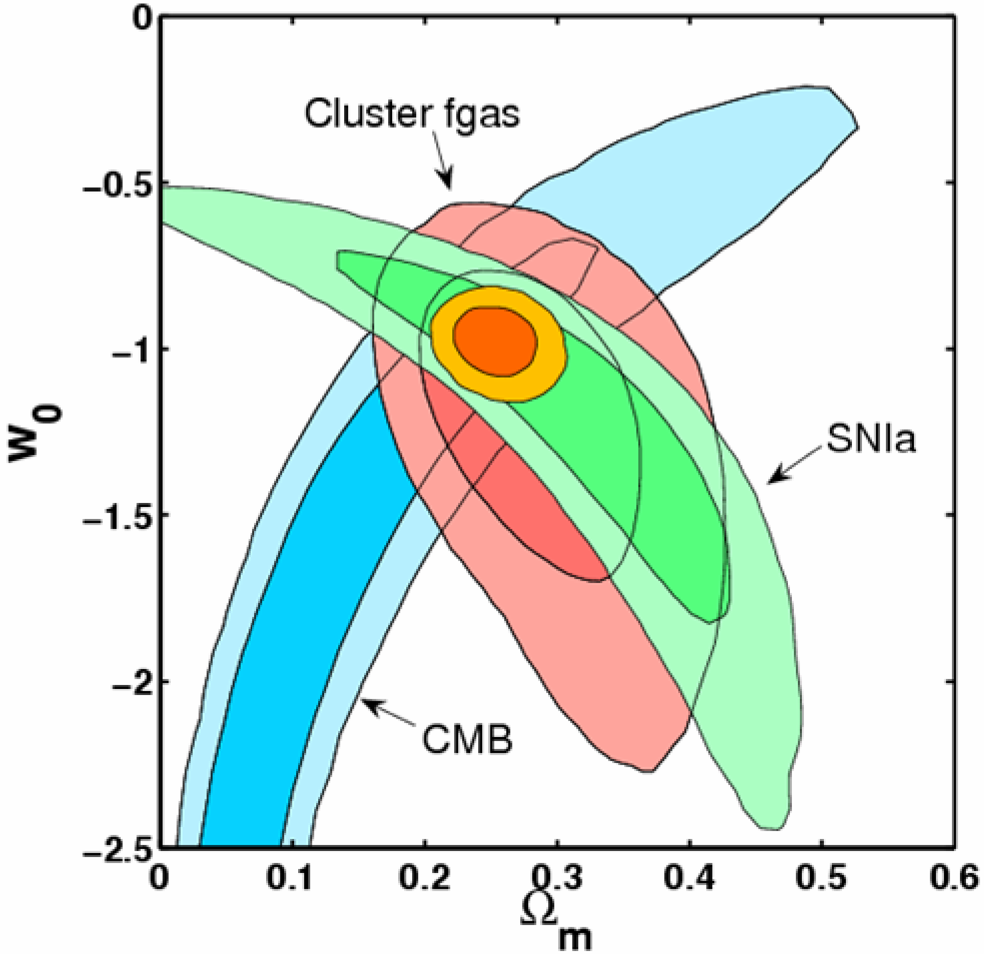
Supernovae data from Davis et al. '07 (192 SNIa, ESSENCE+ SNLS+HST+nearby).

Combined constraint (68%)

$$\Omega_m = 0.275 \pm 0.033$$
$$\Omega_\Lambda = 0.735 \pm 0.023$$

Allen et al 2008

Dark energy equation of state:



Constant w model:

Analysis assumes flat prior.

68.3, 95.4% confidence limits for all three data sets consistent with each other.

Combined constraints (68%)

$\Omega_m = 0.253 \pm 0.021$
$w_0 = -0.98 \pm 0.07$

Note: combination with CMB data removes the need for $\Omega_b h^2$ and h priors.

Con-X and the fgas experiment

Rapetti & Allen 2008 astro-ph (0710.0440)

The fgas experiment and Con-X

Baseline Con-X hardware config. (high throughput, high spectral resolution spatially-resolved X-ray spectroscopy) is well-suited to fgas experiment.

Possible observing plan:

Use ~10% of available time over first 5 years of Con-X mission (12-13Ms).

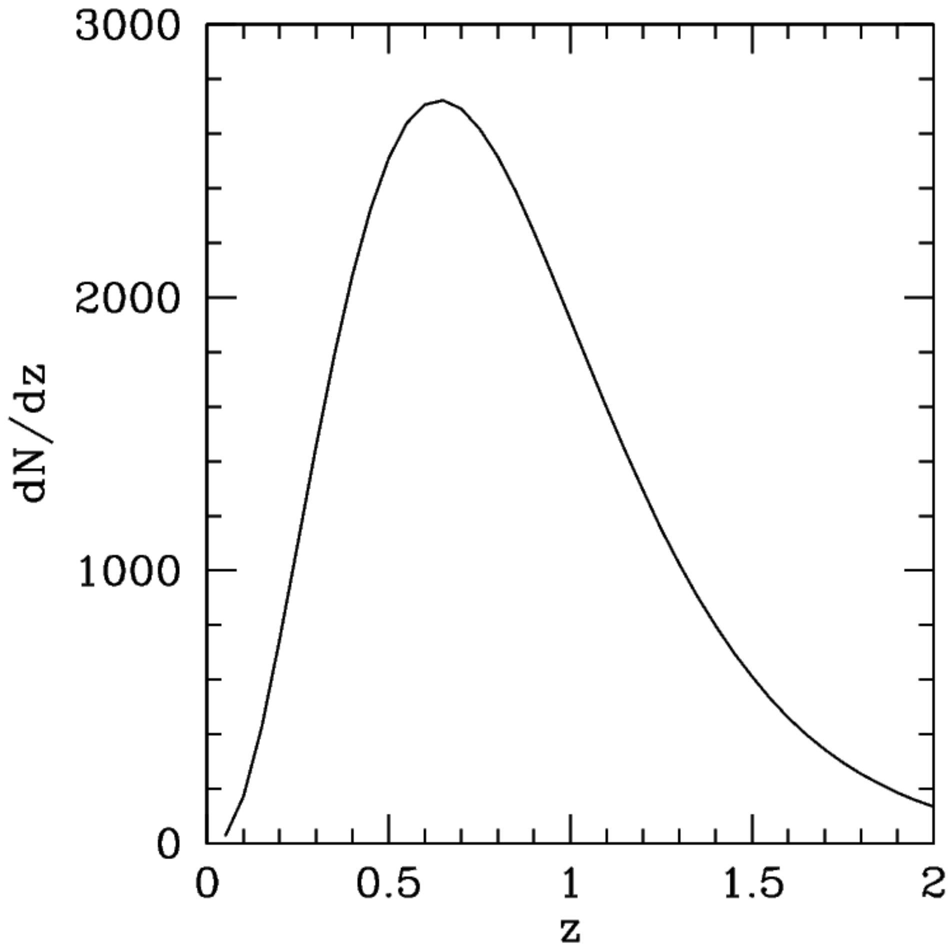
STEP 1: First take ~1ks snapshots of ~2000-3000 most X-ray luminous (or highest integrated SZ flux) clusters detected from precursor X-ray and/or SZ surveys → identify most massive relaxed systems. Morphology + spectroscopy (turbulence). (2-3 Ms total time)

STEP 2: A resulting sample of the `best' 250-500 clusters will then be targeted for, on average, 20-40ks each, allowing us to measure fgas and/or predict the Compton y-parameter to 5% or 3.5% accuracy, respectively. Note 5% accuracy in fgas corresponds to 3.3% in distance) (10 Ms total time)

remember, no scatter observed at 5% level

Redshift distribution of target clusters

The necessary target clusters are out there in the Universe



e.g. assume Con-X targets provided by eROSITA flux limited X-ray survey.

Figure shows kT>5 keV (same kT range as now).

Assume ~1/6 relaxed (c.f. 1/4 at 0.3<z<0.5 in MACS)

$\rightarrow$ ~500 clusters

Note: target density for kT>5keV peaks at z~0.6.

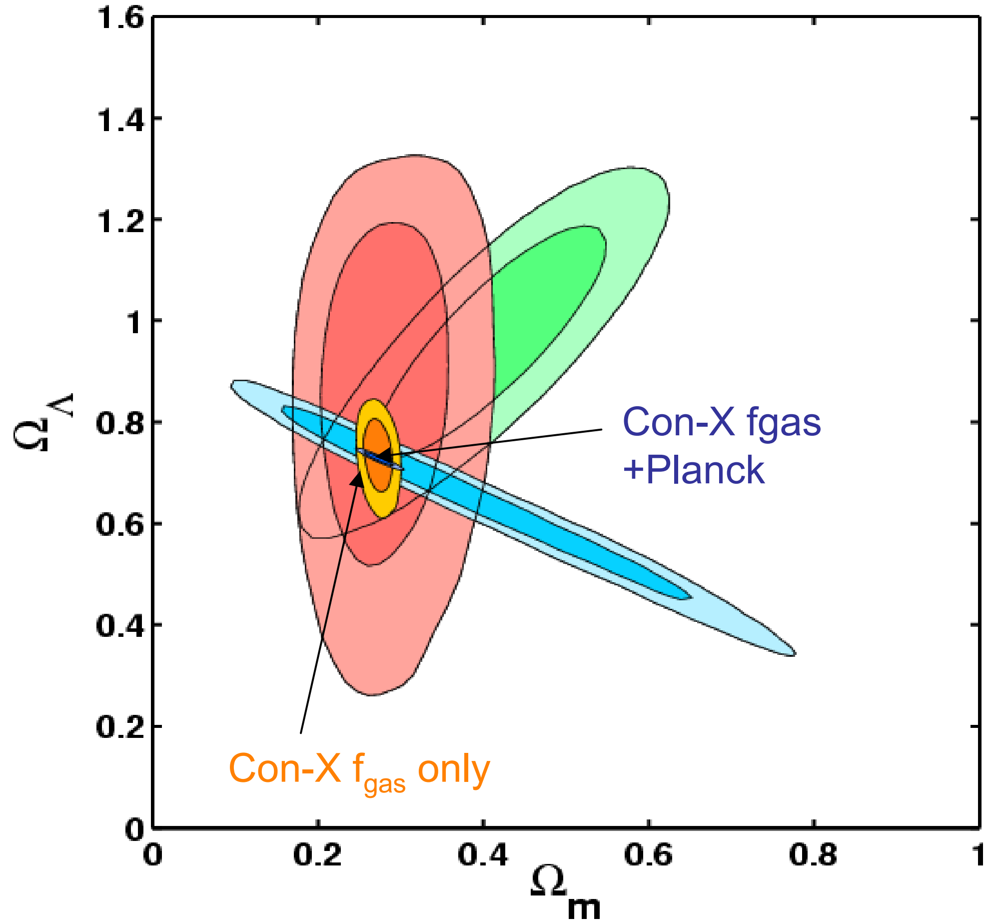
Results achievable with Con-X

Results are presented in the style of the Dark Energy Task Force (DETF) report to allow for direct and easy comparison with other techniques.

Like the DETF, we assume `Planck priors' and present results for `optimistic', `standard' and `pessimistic' systematic allowances. Full MCMC simulations.

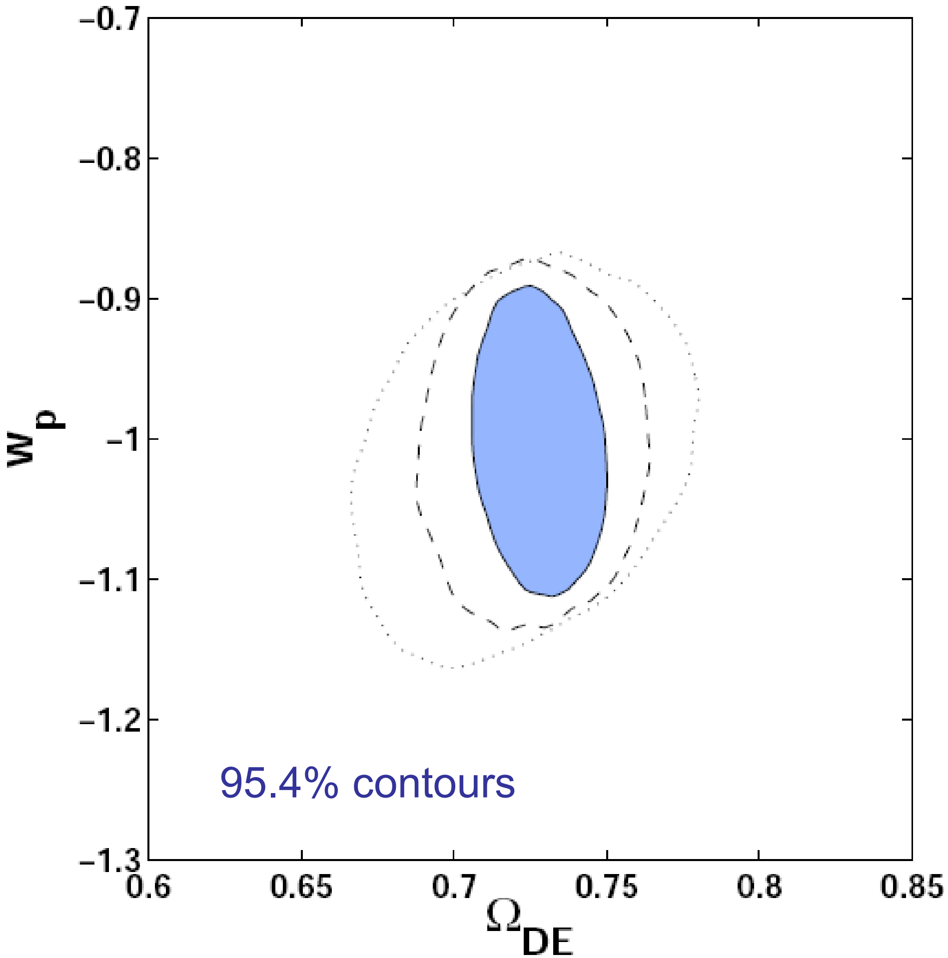
Cluster	Parameter	Allowance (optimistic/standard/pessimistic)	Type
$f_{\rm gas}$ EXPERIMENT			
Calibration/Modelling	K	$1.0 \pm 0.02/\pm 0.05/\pm 0.10$	Gaussian
Non-thermal pressure	γ	$0.96 < \gamma < 1.04/0.92 < \gamma < 1.08$	uniform
Gas depletion: norm.	b_0	$0.82 \times (1 \pm 0.02/\pm 0.05/\pm 0.10)$	uniform
Gas depletion: evol. (linear)	$\alpha_{\rm b}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Gas depletion: evol. (quadratic)	$\beta_{\rm b}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Stellar mass: norm.	s_0	$0.16 \times (1 \pm 0.02/\pm 0.05/\pm 0.10)$	Gaussian
Stellar mass: evol. (linear)	$\alpha_{\rm s}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Stellar mass: evol. (quadratic)	$\beta_{\rm s}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
XSZ EXPERIMENT			
Calibration/Modelling	k_0	$1.0 \pm 0.02/\pm 0.05$	Gaussian
evolution (linear)	$\alpha_{\rm k}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform

Projected Con-X constraints: ΛCDM model



Rapetti & Allen '08

Projected Con-X constraints: DETF figure of merit (FoM)



optimistic (blue) standard (dashed)

$$FoM=[\sigma(w_p)\times\sigma(w_a)]^{-1}$$
$w_p=w(a_p)$; minimal $\sigma(w(a))$.

	$\sigma(\Omega_{DE})$	$\sigma(w_p)$	FoM
Optim.	0.009	0.044	52.4
Pessim.	0.023	0.058	32.6

Comparable constraints (opt./pes.)

	Space	Ground
SNIa	27.0 / 19.1	22.2 / 7.9
BAO	42.2 / 19.8	55.2 / 21.5

Rapetti & Allen '08

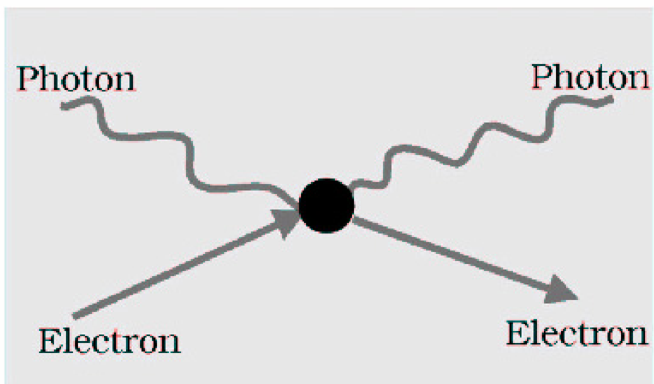
Projected Con-X constraints: full results

Allowances	Run Model	Dark energy parameters $\hat{\sigma}(w_0)$	$\hat{\sigma}(\Omega_{\rm de})$	$\hat{\sigma}(w_{\rm p})$	$\hat{\sigma}(w_{\rm a})$	FoM $[\hat{\sigma}(w_{\rm p}) \times \hat{\sigma}(w_{\rm a})]^{-1}$	ΔFoM/FoM (percentage)
2%	Default	0.100	0.009	0.044	0.43	52.4	–
2%	DE clustering	0.109	0.009	0.044	0.48	46.8	-10.7%
2%	CMB conservative	0.108	0.009	0.045	0.49	44.6	-14.8%
2%	Quadratic	0.116	0.009	0.047	0.50	43.3	-17.4%
2%	250-sample	0.110	0.009	0.047	0.47	45.5	-13.1%
2%	Double γ	0.103	0.012	0.049	0.45	44.6	-14.9%
2%	Adding XSZ	0.097	0.009	0.043	0.43	54.6	+4.2%
5%	Default	0.108	0.015	0.052	0.51	37.4	–
5%	DE clustering	0.119	0.015	0.051	0.59	33.4	-10.7%
5%	CMB conservative	0.115	0.016	0.053	0.58	32.6	-12.8%
5%	Quadratic	0.126	0.014	0.069	0.51	28.7	-23.3%
5%	250-sample	0.119	0.016	0.057	0.55	31.6	-15.4%
5%	Double γ	0.108	0.017	0.054	0.51	36.5	-2.3%
5%	Adding XSZ	0.102	0.014	0.050	0.49	41.2	+10.2%
10%	Default	0.110	0.023	0.058	0.53	32.6	–
10%	DE clustering	0.132	0.022	0.054	0.66	27.9	-14.4%
10%	CMB conservative	0.118	0.026	0.063	0.60	26.6	-18.4%
10%	Quadratic	0.141	0.023	0.102	0.55	17.9	-45.1%
10%	250-sample	0.119	0.024	0.062	0.56	29.0	-11.3%
10%	Double γ	0.110	0.024	0.059	0.53	31.8	-2.5%
10%	Adding XSZ	0.106	0.020	0.055	0.52	34.8	+6.5%

Absolute distances from combined X-ray + SZ studies

The observed SZ flux (radio/sub-mm data) can be expressed in terms of the Compton y-parameter. For a given reference cosmology, the same parameter can also be predicted from X-ray data.

For correct reference cosmology observed and predicted SZ flux should agree.



$$y_{ref} \propto \int n_e T dl$$

$$y_{ref} = y_{obs} k(z) \left[\frac{d_{ref}}{d_{\mathrm{mod}}} \right]^{1/2}$$

Combined cal.+ systematic uncertainties $k(z)=k_0(1+\alpha_k z)$

To date, experiment used to constrain H_0 (e.g. Bonamente et al '06)

Intrinsically less powerful than fgas experiment but provides important complementary information and, in combination with fgas data, allows us to check/relax the need for priors in the anlaysis.

Probing cosmology with X-ray clusters

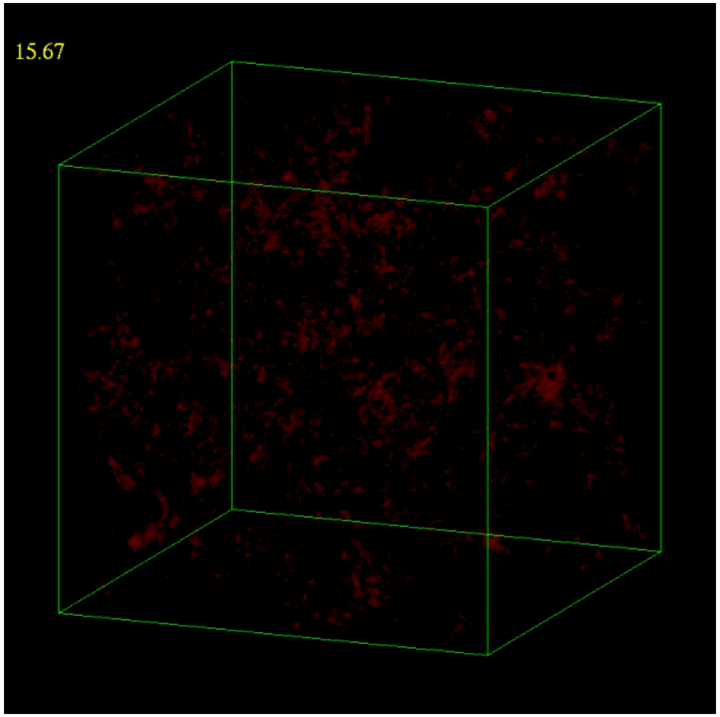
2. The growth of cosmic structure (evolution of the XLF)

Mantz et al. 2008, MNRAS, submitted

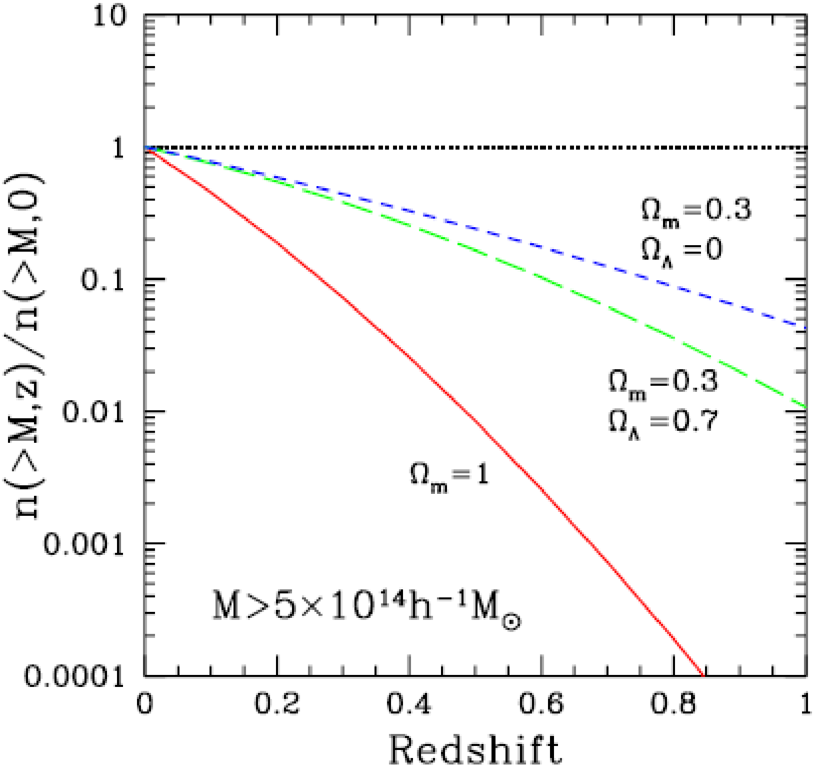
(See also e.g. Henry ’00; Borgani et al ’01; Reiprich & Bohringer ’02; Seljak ’02; Viana et al ’02; Allen et al. ’03; Pierpaoli et al. ’03; Vikhlinin et al. ’03; Schuecker et al ’03; Voevodkin & Vikhlinin ’04; Henry ’04; Dahle ’05; Vikhlinin et al ‘08)

Cluster growth of structure experiments

Moore et al.



Borgani '06



The observed growth rate of galaxy clusters provides (highly) complementary constraints on dark matter and dark energy to those from distance measurements.

Ingredients for cluster growth of structure experiments

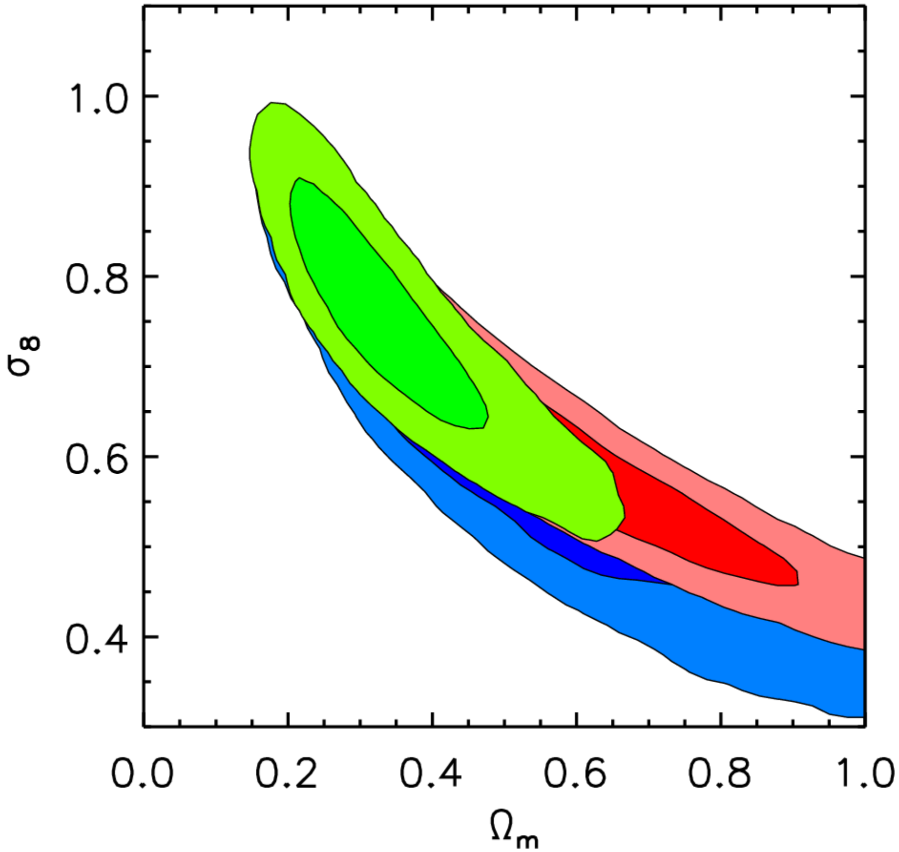
[THEORY] The predicted mass function for clusters, n(M,z), as a function of cosmological parameters (σ_8,Ω_m,w_0, w_a etc) $\leftarrow$ in hand from current + near future numerical simulations (e.g. Jenkins et al. ’01)

[CLUSTER SURVEY] A large, wide-area, clean, complete cluster survey, with a well defined selection function.

Current leading work based on ROSAT X-ray surveys. Future important work based on new SZ (SPT, Planck) and X-ray (eROSITA/Spectrum-X-gamma) cluster catalogues (also optical and lensing surveys).

[SCALING RELATION] A tight, well-determined scaling relation between survey observable (e.g. Lx) and mass, with minimal intrinsic scatter.

Results on σ_8, Ω_m (flat ΛCDM model) CONSERVATIVE



BCS: $\Omega_m = 0.36\ (+0.20, -0.12)$
$\sigma_8 = 0.67\ (+0.14, -0.14)$

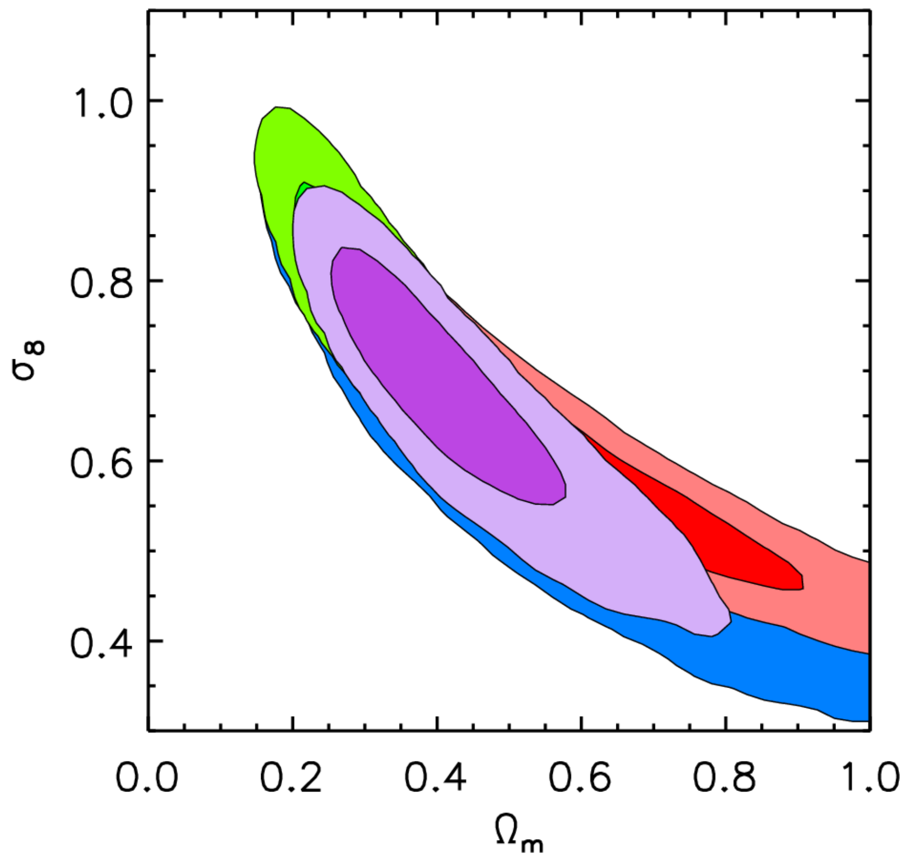
REFLEX: $\Omega_m = 0.31\ (+0.10, -0.07)$
$\sigma_8 = 0.76\ (+0.09, -0.09)$

MACS: $\Omega_m = 0.43\ (+0.26, -0.15)$
$\sigma_8 = 0.63\ (+0.10, -0.14)$

(standard priors included)

Excellent agreement between results from 3 independent X-ray cluster surveys

Current results on σ_8, Ω_m (flat ΛCDM model)



BCS: $\Omega_m = 0.36\ (+0.20, -0.12)$
$\sigma_8 = 0.67\ (+0.14, -0.14)$

REFLEX: $\Omega_m = 0.31\ (+0.10, -0.07)$
$\sigma_8 = 0.76\ (+0.09, -0.09)$

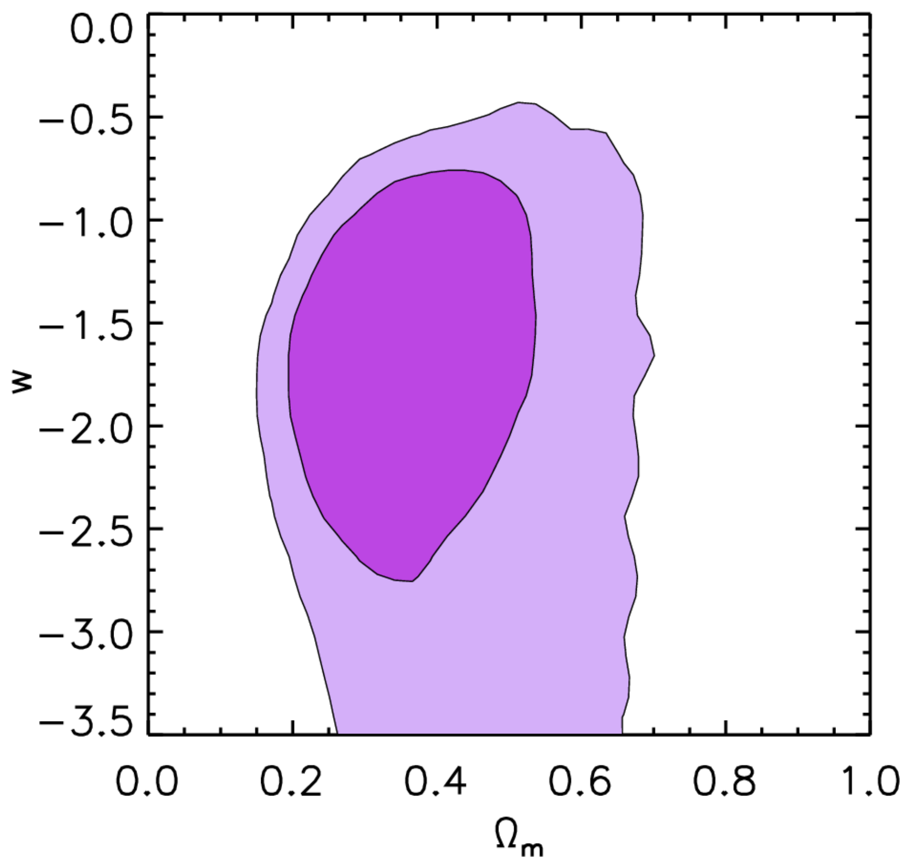
MACS: $\Omega_m = 0.43\ (+0.26, -0.15)$
$\sigma_8 = 0.63\ (+0.10, -0.14)$

Combined constraints (68%)

$\Omega_m = 0.37\ (+0.13, -0.08)$
$\sigma_8 = 0.71\ (+0.07, -0.12)$

Mantz et al 2008

Results on dark energy (CONSERVATIVE)



Flat, constant w model:

REFLEX+BCS+MACS (z<0.7).
242 clusters, Lx>2.55e44 erg/s.
2/3 sky. n(M,z) only.

68.3, 95.4% confidence limits

Marginalized constraints (68%)

Ω_m = 0.35 (+0.14, -0.09)
σ_8 = 0.71 (+0.12, -0.12)
w = -1.5 (+0.6,-0.8)

First constraint on w from a cluster growth of structure experiment

Priors and allowances for systematic uncertainties

Our full analysis includes the following priors and conservative allowances for systematic uncertainties:

1) Cosmological parameters

Hubble constant, h	0.72 ± 0.08 (standard), 0.72 ± 0.24 (weak)
baryon density, $\Omega_b h^2$	0.0214 ± 0.0020 (standard), 0.0214 ± 0.0060 (weak)
spectral index, n_s	0.95 fixed (standard), $0.9<n_s<1.0$ (weak)

2) Jenkins mass function

normalization, A	±20% (standard), ±40% (weak)

3) Mass-luminosity relation

non-thermal pressure bias	25±5% (standard), 25±10% (weak)
non-thermal pressure scatter	15±3% (standard), 15±6% (weak),
evolution of M-L scatter	±20% uniform (standard), ±40% (weak)
non-self similar M-L evolution	±20% uniform (standard), ±40% (weak)

Prospects for future cluster `growth of structure' work

What is the role of Constellation-X?

The uncertainties in cosmological parameters from cluster `growth of structure' work are dominated by uncertainties in the mass-observable relation.

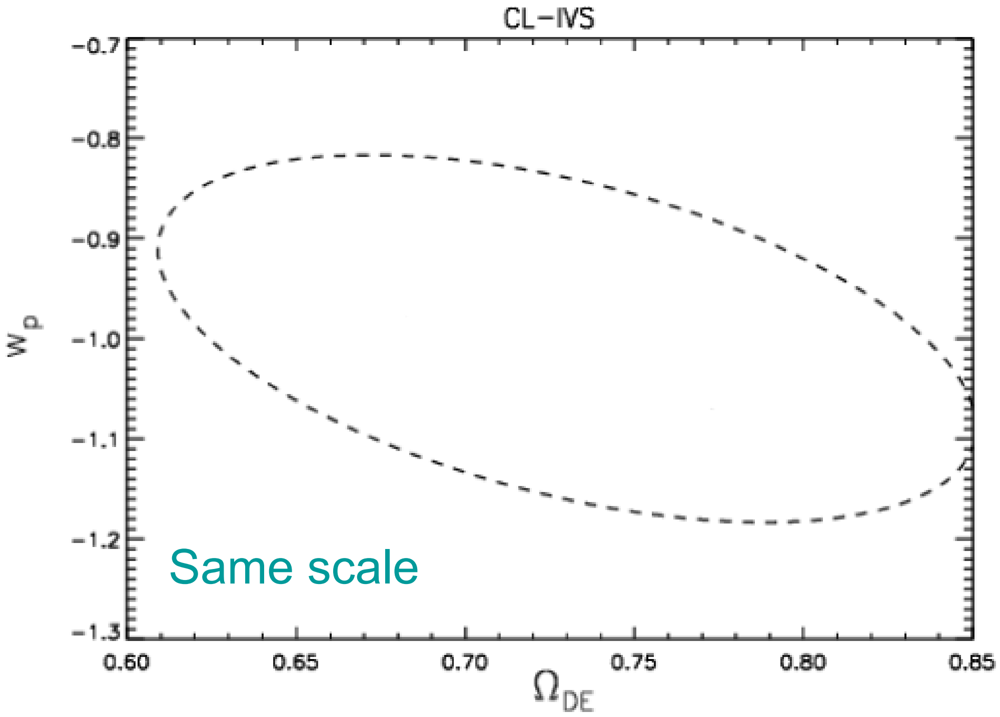
The Dark Energy Task Force (DETF: Albrecht et al '06) consider a future 20000 sq degree X-ray/SZ survey with 30,000 clusters, comparable to that expected from e.g. eROSITA/Spectrum-X-gamma or future large SZ surveys.

They examine the constraints achievable from `growth of structure+spatial clustering' information, both with and without detailed information on the mass-observable relation.

In essence, this shows the difference that follow-up observations with Constellation-X, providing (optimistic) precise mass measurements (few % accuracy) for a small, `fair sample' of survey data (few % of clusters), can make….

Constraints from future cluster surveys I

Option 1: `Self calibration': marginalize over unknown norm/scatter of mass-observable relation (using priors on form of relation) solving for cosmological parameters using only shape of mass (proxy) function + clustering information.



Dark Energy Task Force:

20000 sq degree X-ray/SZ survey. 30000 clusters with M>2.5e14/h Msun.

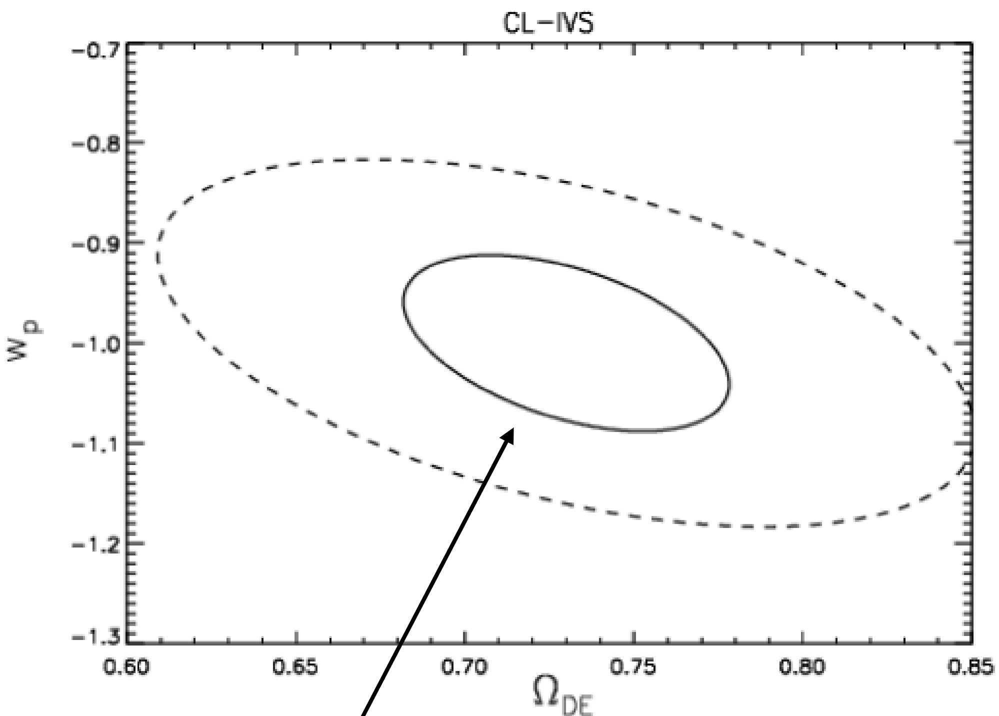
Self calibration only.

Accuracy: $\sigma(w)$ ~ ±0.08
DETF FoM ~ 5-10.

Note: Some other studies provide more optimistic projections but self-calibration requires very detailed (sub %) knowledge of survey characteristics to work well.

Constraints from future cluster surveys 2

Option 2: Use Con-X X-ray data to measure the mass-observable relation for fair sample (e.g. 2%) of clusters + calibrate with simulations. Requires high spectral resolution to map gas motions (primary uncertainty) ← Con-X contribution.



Dark Energy Task Force:

20000 sq degree X-ray/SZ survey. Mass-observable relation for 2% clusters calibrated to ~2 % accuracy.

Accuracy: $\sigma(w) <= \pm 0.04$
DETF FoM >=40

Conclude: Con-X follow-up of small fraction of clusters in future X-ray/SZ surveys can dramatically enhance their power to constrain dark energy.

Conclusions

Con-X can make MAJOR contribution to cosmology circa 2015-2020.

Constraints on dark matter/dark energy from fgas technique comparable to best other planned `Stage IV' dark energy experiments (SNIa, BAO, weak lensing). Detailed simulations $\rightarrow$ DETF figure of merit 20-50.

Con-X should also make important contribution to `growth of structure' work, enabling the extraction of more information from new X-ray/SZ cluster surveys.

Not just `a bigger light bucket': calorimeter data directly adresses one of dominant systematic uncertainties - the level of non-thermal pressure support due to turbulent/bulk motions in cluster gas (as a fn. of redshift and dynamical state).

Excellent synergies with future X-ray, SZ, optical, near-IR surveys, as well as deep, targeted multiwaveband observations (JWST, ALMA etc).